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LITERATURE REVIEW OF DISPLACEMENT VENTILATION

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EXECUTIVE SUMMARY

This report reviews the literature about displacement ventilation. It begins with a summary of literature search methods and the number of papers and articles found. In summary, displacement ventilation systems may provide better indoor air quality than conventional mixing ventilation systems and maintain a thermally comfortable indoor environment. Displacement ventilation keeps the mean age of air in a room younger than does the conventional mixing ventilation. Due to the potential existence of draft and the large temperature stratification with displacement ventilation, a designer needs a careful attention to the air temperature distribution in spaces. A recent design guideline developed by Chen and Glicksman (2003) can be used for the design of the displacement ventilation systems for buildings in the U.S.

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I. INTRODUCTION

1.1. Sources Searched and Keywords

Various sources and search engines were used to find the technical research and literature by using specific keywords to search for the relevant reports or browsing through the list of documents. First, the 78 references from the book, “System Performance Evaluation and Design Guidelines for Displacement Ventilation” by Chen and Clicksman (2003), were used to begin the literature search. Their references include papers, articles, and web sites presenting major contributions to the understanding and development of the displacement ventilation technology and design. Other literature search methods were utilized. Below is the list of sources:

ASHRAE abstract archives:
ASHRAE transactions and journal papers are main sources about the DV systems. (More than 60 papers found)

Elsevier Literature Search Engine:
Key word: Displacement Ventilation (26 papers found)

The search engines and publication lists used are as follow:
- ASHRAE Abstract Archives
- ASHRAE Bookstore
- ScienceDirect (ELSEVIER Journals)
- UMI Digital Dissertations
- Wilson Abstracts

This report includes a general description of displacement ventilation, several findings, and a list of technical research and literature of the displacement ventilation systems.

II. FINDINGS

The following is a summary of discussion points derived from a review of the literature.

2.1. Temperature Distribution

- Air temperature in a space varies linearly with space height in the stratified zone and is nearly constant in horizontal directions except in the region near the supply diffusers.
- Skistad (1994) showed that displacement ventilation is more suitable for high spaces, such as concert halls and workshops.
- The performance of diffusers is critical to avoid drafts near the diffusers. Skaret (1985) and Nielsen et al. (1988) showed the impact of supply diffusers whereby increasing the entrainment of room air can decrease the temperature gradient in the occupied zone.
- Two important parameters to evaluate the performance of displacement ventilation are the air temperature near the floor and vertical temperature gradient. It is relatively easy to measure the temperature near the floor, but difficult to calculate the gradient.

2.2. Airflow Distribution

- The velocity of airflow near a diffuser is dependent on the flow rate from the diffuser, the temperature difference, and the diffuser type.
- The thermal plumes and supply air from diffusers play an important role in the displacement ventilation.
- It is necessary to carefully control the velocity of airflow in the occupied zone especially near the diffusers to avoid drafts that cause discomfort for occupants.

2.3. Contaminant Distribution

- Contaminant distribution is dependent on contaminant source type and location, human body convection, wall surface temperature, space height, and etc.
- Heiselberg and Sandberg (1990) showed that the occupied zone with displacement ventilation has a lower contaminant concentration level than that in the upper zone.
- The inhaled air is cleaner than the air at the same height since the upward free convection around a person brings the air from a lower level to the breathing zone.
- It is more difficult to predict the contaminant distribution than to calculate air temperature and airflow distribution.

2.4. Indoor Air Quality (IAQ) and Comfort

- Achieving a high indoor air quality environment is the main purpose for using displacement ventilation.
- Two main causes of discomfort with displacement ventilation are vertical temperature gradient and draft.

- Supply flow rate needs to be increased to reduce the temperature gradient, but it results in a high air velocity at the floor level and a high draft risk.
- Displacement ventilation can remove more cooling loads when the cooled ceiling panels are combined. Low flow rate fans may decrease the temperature gradient and extend the application range.

2.5. Energy and Cost

- For the evaluation of energy consumption of displacement ventilation, the numerical simulation is the main method, since yearly measurements are too expensive and time consuming.
- Energy consumption of displacement ventilation is similar to that of conventional mixing systems, sometimes smaller or larger, depending on the control strategies and the HVAC systems.
- Displacement ventilation is attractive to the core region in a building since no heating is needed. However, the perimeter zones require high cooling energy.
- The supply air temperature of displacement ventilation is 4 ºF to 6 ºF higher than that of conventional mixing ventilation, which means more natural cooling.

III. EVALUATION OF DISPLACEMENT VENTILATION

3.1. General Description of Displacement Ventilation (DV)

Displacement Ventilation (DV) is one of the concepts for the supply of conditioned air and ventilation of buildings. Air is introduced at low velocity through floor terminals or other diffusers. As shown in Figure 1, the air is lifted up by the heat sources in the room, passes through the occupied zone, and is exhausted at high level. This system has been used quite commonly in Scandinavia for the last two decades.

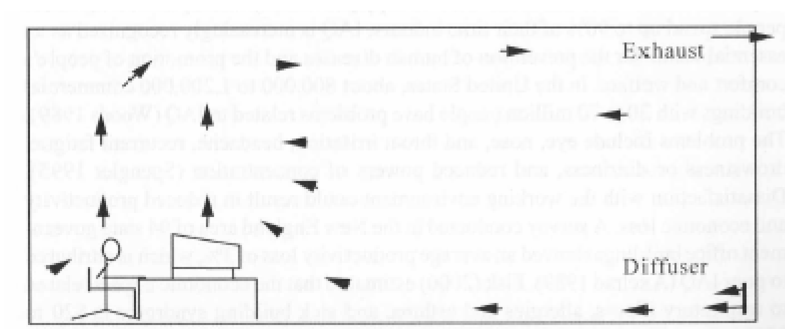

Figure 1. Sketch of displacement ventilation (Chen and Glicksman, 2003).

3.2. Three Different Types of Displacement Ventilation

Chen and Glicksman (2003) categorized displacement ventilation into three different types: 1) traditional displacement ventilation, 2) displacement ventilation with a chilled ceiling panel, and 3) displacement ventilation with a raised floor. These are dependent upon the method used to deliver incoming air. For the traditional displacement ventilation systems, the incoming air is released from wall ducts that are typically located under windows. A chilled ceiling panel can be used associated with the conventional displacement ventilation system. This combined system may provide a comfort environment at a higher range of cooling load than the conventional-only system (Niu, 1994). The displacement ventilation system with a raised floor uses plenums under the floor to supply air using in/above-floor fans.

3.3. Benefits and Barriers of Displacement Ventilation

Displacement ventilation systems are quieter than conventional overhead systems. They provide better indoor air quality, since ventilation efficiency is better than conventional systems. Displacement systems are appropriate in spaces where high ventilation is required, such as classrooms, conference rooms, and offices.

There are two main concerns in displacement ventilation: 1) 'draft,' defined as unwanted local cooling of the body near the floor caused by air movement and 2) vertical temperature gradient. To decrease the discomfort caused by the large vertical temperature gradient, one can increase the supply flow rate. However, it results in the high air velocity at the floor level, which leads to a high draft risk.

Also, most studies indicated that the displacement ventilation systems can only provide acceptable comfort if the corresponding cooling load is less than about 13 Btu/h-sf or 40 W/m2. When higher ceiling heights are applied, the displacement ventilation systems are capable of removing larger cooling loads (Skistad, 1994). Niu (1994) showed that if the cooled ceiling is combined with the displacement ventilation, a comfort environment can be achieved with a cooling load up to 16 Btu/h-sf or 50 W/m2. However, the displacement systems with the cooled ceiling panel may result in downdrafts in the occupied zone. For that reason, the minimum surface temperature should be 59 ºF or 15 ºC and the ratio of panel area to ceiling area should be less than a certain amount. To avoid condensation on the panel surface, a minimum surface temperature is also required (Chen and Glicksman, 2003).

The energy consumption of displacement systems is about the same with that of conventional mixing systems, although there are differences depending on the control strategies and the type of HVAC systems. In the energy calculation by Niu (1994), it is shown that the annual energy consumption of displacement ventilation with a water-cooled ceiling system is almost the same as that of an all-air system. Seppanen et al. (1989) showed that displacement ventilation systems do not have much influence on energy consumption; however, the first cost is much higher than the mixing systems when the cooling panels are required to meet the cooling loads that exceed 13 Btu/h-sf or 40 W/m2.

3.4. Design Guidelines for the Displacement Ventilation Systems

Skistad (1994) had developed and introduced a design guideline for the displacement ventilation systems, which consists of five steps below.

- Step 1) Determine the required airflow rate for removal of surplus heat based on the cooling load and the air temperature differences between supply and exhaust openings.
- Step 2) Find the required airflow rate for removal of pollutants according to ventilation standards.
- Step 3) Choose the larger of the two flow rates determined at Steps1 and 2 as the ventilation rate.
- Step 4) Determine supply air temperature under assumptions of $\theta_f = 0.5$ and constant vertical temperature gradient.
- Step 5) Choose supply diffusers according to the data provided by manufactures in order to avoid drafts.

However, based on a review and a survey among architects and energy consumption in the U.S. (Chen et al., 1999), Chen and Glicksman (2003) concluded that there are no design guidelines that can be used with confidence in U.S. Therefore, they developed a ten-step design procedure for displacement ventilation systems. Below is a brief description of each step.

- Step 1) Judge the applicability of displacement ventilation.
- Step 2) Calculate summer design cooling load.
- Step 3) Determine the required flow rate of the supply air for summer cooling.
- Step 4) Find the required flow rate of fresh air for acceptable indoor air quality.
- Step 5) Determine the supply airflow rate.
- Step 6) Calculate the supply air temperature.
- Step 7) Determine the ratio of the fresh air to the supply air.
- Step 8) Select supply air diffuser size and number.
- Step 9) Check the winter heating situation.
- Step 10) Estimate the first costs and annual energy consumption.

IV. SUMMARY

Displacement ventilation is an air distribution system where air comes in at floor level and rises up to exhaust outlets at the upper level of the walls or ceiling. Air is delivered to interior rooms through diffusers on the floor-level, displacing upper air, which is exhausted through ceiling-level vents. Displacement ventilation systems basically utilize 100% outside air, and, as a result, air pollutants generated within a room are removed at the source and are not re-circulated. In addition, heat generated by ceiling level lights is removed, and thus heat is not included when estimating building cooling loads.

Displacement ventilation has been used mainly in Scandinavian countries that have moderate temperatures and even lower temperatures than many U.S. cities. Therefore, the cooling load could be higher in the U.S. than in Scandinavian countries (Chen et al., 1999). In many U.S. offices, cooling is needed year round in the core spaces that are totally isolated from the ambient climate. Displacement ventilation is a great potential for such places.

Displacement ventilation has two main concerns: ‘draft’ and ‘vertical temperature gradient’. These should be carefully considered in design. The displacement ventilation systems consume slightly smaller energy or almost the same compared to the energy used by the conventional mixing ventilation systems. The first costs are also about the same between two different system types, but the displacement ventilation systems may require slightly more cost for initial installation because of a separate heating system for the perimeter zones of a building.

Chen and Glicksman (2003) developed the most complete design guideline for displacement ventilation systems applicable to the U.S. climate conditions. The purpose of the guideline is to help determine the key parameters in the displacement ventilation systems, such as ventilation rate, location and type of supply diffuser, and supply air temperature.

IV. REFERENCES

Chen, Q., Glicksman, L.R., Yuan, X., Hu, S. Yang, X. 1999. Performance evaluation and development of design guidelines for displacement ventilation, Final report for ASHRAE RP-949. Department of Architecture, Massachusetts Institute of Technology, Cambridge, Mass., 230 pages.

Chen, Q., Glicksman, L. 2003. System performance evaluation and design guidelines for displacement ventilation. American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc. Atlanta, GA.

Heiselberg, P., Sandberg, M. 1990. Convection from a Slender Cylinder in a Ventilated Room. Proceedings of ROOMVENT '90. *International Conference on Engineering Aero – and Thermodynamics of Ventilated Rooms,* Oslo, Norway.

Nielsen, P.V., Hoff, L., Pedersen, L.G. 1988. Displacement Ventilation by Different Types of Diffusers. *Proceedings of the 9th AIVC Conference,* Warwick.

Niu, J. 1994. Modeling of Cooled-Ceiling Air-Conditioning Systems *Ph.D. Dissertation,* Delft University of Technology, The Netherlands.

Seppanen, O.A., Fisk, W.J., Eto, J., Grimsrud, D.T. 1989. Comparison of conventional mixing and displacement air-conditioning and ventilating systems in U.S. commercial buildings. *ASHRAE Transactions,* Vol. 95, Pt. 2.

Skaret, E. 1985. *Ventilation by Displacement – Characterization and Design Application. Ventilation '85*. Goodfellow (ed.), Elsevier Science Publishers: B.V. Amsterdam.

Skistad, H. 1994. *Displacement Ventilation.* Research Studies Press Ltd.: Taunton, Somerset, England.

V. ANNOTATED BIBLIOGRAPHY

Akimoto, T., Nobe, T., Takebayashi, Y. 1995. Experimental study on the Floor-supply displacement ventilation system. *ASHRAE Transactions*, Vol. 101, Pt. 2, pp. 912-925.

This study investigates the effects of a floor-supply displacement ventilation system with practical indoor heat loads. For the experiments, an experimental chamber (35.2 m^2) located in a controlled environmental chamber was used. Temperature distributions were measured at seven heights throughout the experimental chamber for each test condition. Data were analyzed to observe thermal stratification as affected by lighting, occupants, and heat loads (personal computers), and its disruption caused by walking and change of air volume. In addition, air flow characteristics and ventilation efficiencies were investigated using a smoke machine, tobacco smoke, dust for industrial testing, and a tracer gas (CO_2) step-up procedure.

Alamdari, F., Butler, D.J.G., Grigg, P.F., Shaw, M. R. 1998. Chilled ceilings and displacement ventilation. *Renewable Energy*, Vol. 15, Issues 1-4, pp. 300-305.

Abstract: Displacement ventilation and chilled ceiling systems have been promoted as being 'greener' alternatives to other common forms of air conditioning system. They have been viewed by some of the building services industry as a welcome departure from the traditional 'North American' systems of air conditioning most frequently adopted to date, and could be viewed as a more suitable alternative for use in the moderate climatic conditions of the UK. This paper reviews some of the authors' recent and current work on the performance of these systems in office environments.

Behne, M. 1999. Indoor air quality in rooms with cooled ceilings: Mixing ventilation or rather displacement ventilation? *Energy and Buildings*, Vol. 30, Issue 2, pp. 155-166.

Abstract: Experimental investigations and practical experiences in Europe have proved that hydronic cooled ceilings are able to remove high cooling loads without impairing thermal comfort. As hydronic cooled ceilings cannot remove latent loads and pollutants, (e.g., CO_2, VOCs, odors) additional ventilation must be applied. Often, displacement ventilation is used, which is able to provide lower pollutant levels in the occupation zone than mixing flow systems, if the occupants are causing most of the pollution. Unfortunately, the advantage of the displacement flow, in respect to the air quality, can vanish when cooled ceilings are used to remove the major part of the sensible cooling load. For these applications, a combination of a cooled ceiling with a mixing ventilation system might be more appropriate. This paper presents the results of an investigation examining the distribution of tracer gas in a test chamber which is equipped with a radiant cooled ceiling. There is both a displacement flow system and a mixing flow system available, so that the concentrations of the tracer gas within the occupation zone characterizing the air quality can be compared directly and evaluated under similar conditions. The vertical air temperature rise is taken into consideration as well, as it influences the displacement flow and is an important issue for assessing thermal comfort.

The results show the interaction of the portion of the cooling load being removed by the supply air, the air quality in the occupied zone and the vertical air temperature rise. The figures and tables presented show which of the two supply air systems investigated have advantages over the other.

Brohus, H., Nielsen, P.V. 1996. Personal exposure in displacement ventilated rooms. *Indoor Air,* Vol. 6, pp. 157-167.

This paper examines different aspects of personal exposure at different stratification heights in a displacement ventilated room. For the experiments, a thermal manikin was used to measure personal exposure. The results show that the flow in the boundary layer around a person is able to entrain and transport air from below the breathing zone to a great extent, thus improving the quality of the inhaled air. A personal exposure model for the displacement ventilated room is also proposed. The model takes the concentration gradients as well as the influence of the human thermal boundary layer into account.

Cehlin, M., Moshfegh, B., Sandberg, M. 2002. Measurements of air temperatures close to a low-velocity diffuser in displacement ventilation using an infrared camera. *Energy and Buildings*, Vol. 34, Issue 7, pp. 687-698.

Abstract: The near zone of supply air diffusers is very critical for the indoor climate. Complaints of drafts are often associated with low-velocity diffusers in displacement ventilation because the air is discharged directly into the occupied zone. Today, the knowledge of the near zone of these air supply diffusers is insufficient, causing an increased need for better measuring methods and representation of the occupied zone. A whole-field measuring technique has been developed by the authors for visualization of air temperatures and airflow patterns over a large cross-section. In this particular whole-field method, air temperatures are measured with an infrared camera and a measuring screen placed in the airflow. The technique is applicable to most laboratory and field test environments. It offers several advantages over traditional techniques; for example, it can record real-time images within large areas and capture transient events. The purpose of this study was to conduct a parameter and error analysis of the proposed whole-field measuring method applied to a flow from a low-velocity diffuser in displacement ventilation. A model of the energy balance, for a solid measuring screen, was used for analyzing the influence of different parameters on the accuracy of the method. The analysis was performed with respect to the convective heat transfer coefficient, emissivity, screen temperature and surrounding surface temperatures. Theoretically, the temperature difference between the screen and the ambient air was found to be 0.2-2.4 ºC for the specific delimitation in the investigation. However, after applying correction, the maximum uncertainty of the predicted air temperature was found to vary between 0.62 and 0.98 ºC, due to uncertainties in estimating parameters used in the correction. The maximum uncertainty can be reduced to a great extent by estimating the convective heat transfer coefficient more accurately and using a screen with rather low emissivity.

Chen, Q., Kooi van der, J. 1988. ACCURACY - a program for combined problems of energy analysis, indoor airflow and air quality. *ASHRAE Transactions,* Vol. 94, No. 2, pp. 196-214.

A new, user-friendly personal computer program, ACCURACY, was introduced. The program is constructed for energy analysis, room air temperature, and contamination field predictions. In addition, the program is a coupling of a cooling load program and an airflow program. For the calculation, room energy balance method that uses z-transfer functions and window energy balance equations for heat transfer through enclosures were used. Further capabilities of the program will cover the conservation of energy and contaminant concentration using airflow patterns, the influence of the room air supply system on temperature distribution, and indoor air quality and energy consumption.

Chen, Q., Kooi van der, J., Meyers, A. 1988. Measurement and computations of ventilation efficiency and temperature efficiency in a ventilated room. *Energy and Buildings,* Vol. 12, No. 2, pp. 85-99.

This paper presents the study of the air movement and contamination distributions in the room with ventilation. The study was conducted both experimentally and numerically. The experiment is performed in a full-scale climate room with different air supply systems, heat gain from the ventilation blinds and ventilation rates. The measured values are room air flow patterns and air temperature, velocity and contamination concentration fields, etc. As numerical simulation, the airflow computer program PHOENICS and the cooling load program ACCURACY have been applied. The results show that the agreement between the numerical simulations and the measurements are good. The ventilation efficiency and temperature efficiency which are used for evaluation of indoor air quality and energy consumption are reported in each case.

Chen, Q. 1996. Prediction of room air motion by Reynolds-stress models. *Building and Environment, Vol.* 31, No. 3, pp. 233-244.

Typical airflow in a room is predicted using Reynolds-stress models (two isotropization of production models and a quasi-isotropic model) and the standard $k — \epsilon$ model. Various flow patterns such as natural convection, forced convection and mixed convection in a room and an impinging jet flow were studied. In addition, the experimental data was validated from related literature review. The results show that the computations and the experimental data are in agreement for the mean air velocities, but less satisfactory for the turbulent quantities. The performance of the three Reynolds-stress models is similar, they all predict anisotropic turbulence and secondary recirculation existing in a room airflow for which the $k — \epsilon$ model fails. However, the Reynolds-stress models require additional computing effort compared to the $k — \epsilon$ model.

Gan, G. 1995. Numerical investigation of local thermal discomfort in offices with displacement ventilation, *Energy and Buildings*, Vol. 23, Issue 2, pp. 73-81.

Abstract: Local thermal discomfort in offices with displacement ventilation is investigated using computational fluid dynamics. The standard k-e turbulence model is used for the prediction of indoor air flow patterns, temperature and moisture distributions, taking into account heat transfer by conduction, convection and radiation. The thermal comfort level and draught risk are predicted by incorporating Fanger's comfort equations in the airflow model. It has been found that, for sedentary occupants with summer clothing, common complaints of discomfort in offices ventilated with displacement systems resulted more often from an unsatisfactory thermal sensation level than from draught alone. It is shown that thermal discomfort in the displacement-ventilated offices can be avoided by optimizing the supply air velocity and temperature. It is also shown that optimal supply air conditions of a displacement system depend on the distance between the occupant and the air diffuser.

Gan, G. 1996. Numerical Investigation of local thermal discomfort in offices with displacement ventilation, *Fuel and Energy*, Vol. 37, Issue 2, p. 133.

Abstract: Local thermal discomfort in offices with displacement ventilation is investigated using computational fluid dynamics. The standard k-e turbulence model is used for the prediction of indoor air flow patterns, temperature and moisture distributions, taking into account heat transfer by conduction, convection and radiation. The thermal comfort level and draught risk are predicted by incorporating Fanger's comfort equations in the airflow model. It has been found that, for sedentary occupants with summer clothing, common complaints of discomfort in offices ventilated with displacement systems resulted more often from an unsatisfactory thermal sensation level than from draught alone. It is shown that thermal discomfort in the displacement ventilated offices can be avoided by optimizing the supply air velocity and the temperature.

Heiselberg, P., Sandberg, M. 1990. Convection from a slender cylinder in a ventilated room. *Proceedings of ROOMVENT '90: International Conference on Engineergin Aero- and Thermodynamics of Ventilated Rooms*, Oslo, Norway.

This paper deals with some of the effects of persons present in a displacement ventilated room, especially the effect on the contaminant distribution. It was reported that the contaminant distribution showed a clear stratification between clean and contaminated air. It was also found that the convective flow at the heat source as well as the flow at the walls was influencing the level of stratification.

Hunt, G.R., Linden, P.P. 1999. The fluid mechanics of natural ventilation--displacement ventilation by buoyancy-driven flows assisted by wind, *Building and Environment,* Vol. 34, Issue 6, pp. 707-720.

Abstract: This paper describes the fluid mechanics of natural ventilation by the combined effects of buoyancy and wind. Attention is restricted to transient draining flows in a space containing buoyant fluid when the wind and buoyancy forces reinforce one another. The flows have been studied theoretically and the results compared with small-scale laboratory experiments. Connections between the enclosure and the surrounding fluid are with high-level and low-level openings on both windward and leeward faces. Dense fluid enters through windward openings at low levels and displaces the lighter fluid within the enclosure through high-level, leeward openings. A strong, stable stratification develops in this case and a displacement flow is maintained for a range of Froude numbers. The rate at which the enclosure drains increase as the wind-induced pressure drops between the inlet and outlet is increased and as the density difference between the exterior and interior environment is increased. A major result of this work is the identification of the form of the nonlinear relationship between the buoyancy and wind effects. It is shown that there is a Pythagorean relationship between the combined buoyancy and wind-driven velocity and the velocities which are produced by buoyancy and wind forces acting in isolation. This study has particular relevance to understanding and predicting the air flow in a building which is night cooled by natural ventilation, and to the flushing of gas from a building after a leak.

Li, Y., Sandberg, M., Fuchs, L. 1992. Vertical Temperature Profiles in Rooms Ventilated by Displacement: Full-Scale Measurement and Nodal Modelling. *Indoor Air*, Vol. 2, pp. 225-243.

Measurement of the vertical temperature profiles in a full-scale office room ventilated by displacement is presented. To identify the effects of thermal radiation, different wall radiative emissivities have been employed. Two new nodal models (i.e., a four-node model and a multi-node model), are proposed to predict the temperature profile based on the flow and thermal characterization in the room. The results show that the agreement between the models and the experiments are fairly good. The calculated results are applied to show that the temperature profile is influenced considerably by the heat conduction through the walls and the thermal radiation between the wall surfaces. The models developed can be used for design purposes and to supply the thermal boundary conditions in a CFD code.

Loveday, D.L., Parsons, K.C., Taki, A.H., Hodder, S.G. 2002. Displacement ventilation environments with chilled ceilings: thermal comfort design within the context of the BS EN ISO7730 versus adaptive debate. *Energy and Buildings*, Vol. 34, Issue 6, pp. 573-579.

Abstract: The current design standard BS EN ISO7730 [Moderate thermal environments--determination of the PMV and PPD indices and specification of the conditions for thermal comfort, International Standards Organisation (1995)] is based upon the work of Fanger and essentially comprises a steady-state human heat balance model that leads to a prediction of the sensation of human thermal comfort for a given set of thermal conditions. The model was derived from laboratory-based measurements conducted in the mid-1960s in relatively 'conventional' environments. However, a chilled ceiling operated in combination with displacement ventilation represents a more sophisticated environment as compared with the original conditions in which the Fanger model was derived. This raised a question about the applicability of the current standard when designing for thermal comfort in offices equipped with chilled ceiling/displacement ventilation systems. This paper presents findings from an EPSRC-funded study that sought to answer the above question. Human test subjects (184 in total) carried out sedentary office-type work in a well-controlled environmental test room that simulated an office fitted with the above system. Measurements of environmental variables were taken at a number of locations near the subjects, each of whom wore a typical office clothing ensemble. The reported thermal comfort sensations were compared with values predicted from BS EN ISO7730 over a range of system operating conditions. It was shown that the current standard BS EN ISO7730 may be used, without modification, when designing for the thermal comfort of sedentary workers in offices equipped with chilled ceiling/displacement ventilation systems. These findings are interpreted within the context of a proposed modification to thermal comfort design standards that includes adaptive effects, and the influence of BS EN ISO7730 on the development of other radiant surface/displacement ventilation configurations is discussed.

Mattssson, M., Sandberg, M. 1994 Displacement ventilation-Influence of physical activity. *ROOMVENT '94,* Krakow, Poland.

This report presents the influence of physical activity on the ventilation process in a displacement ventilated room. It is reported that a stronger temperature gradient in the room caused better efficiency of the displacement ventilation system and less sensitivity to manikin movements.

Melikov A.K., Nielsen, J.B. 1989. Local thermal discomfort due to draught and vertical temperature difference in rooms with displacement ventilation. *ASHRAE Transactions,* Vol. 95, No. 2, pp. 1050-1057.

This paper presents the evaluations of the thermal comfort conditions in 18 spaces with displacement ventilation. The evaluations include the estimation of the risk of draught and local discomfort due to vertical temperature difference by comprehensive measurements of mean velocity, turbulence intensity and air temperature. The results indicate that there was a high risk of draught and vertical temperature difference, varying substantially in the occupied zone, in some of the spaces. In several cases there was a potential risk of combined discomfort due to draught and vertical temperature difference.

Mundt, E. 1990. Convective flow above common heat source in rooms with displacement ventilation. *Proceedings of International Conference on Engineering Aero-and Thermodynamics of Ventilated Room, ROOMVENT '90,* Oslo, Norway.

Abstract: That convection flows from different heat sources in a room is the driving force for displacement ventilation. The volumes of these flows have to be known in order to see if the ventilation will behave as expected. Convection flows from different heat sources in a surrounding with an even temperature have earlier been investigated. However the convection flows in surroundings with temperature gradients are not as well known. In rooms with displacement ventilation there is always a temperature gradient. The temperature gradients are dependent on the geometry of the room, the internal loads and the ventilation flow. This paper presents a method to calculate the gradients in the room, which have been experimentally proved. It also presents measurements of the air volume flows in plumes above common heat sources in rooms with different temperature gradients.

Mundt, E. 1995. Displacement ventilation systems--Convection flows and temperature gradients. *Building and Environment*, Vol. 30, Issue 1, pp. 129-133.

Abstract: Temperature gradients and convection flows are of great importance in sizing a displacement ventilation system. The temperature gradient is the determining factor for the use of this type of ventilation in which the convection flows influence the air quality in the room. Models for the calculation of the temperature gradients and the convection flows from different heat sources are presented here and compared with experimental data.

Murakami, S., Kato, S., Zeng, J. 1997. Flow and temperature field around human body with various room air distribution-CFD study on computational thermal manikin: Part 1. *ASHRAE Transactions*, Vol. 103, No. 1. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Abstract: The aim is to develop a computational thermal manikin to accurately predict the thermal comfort of a human in a room by computer simulation. The human's thermal sensation directly depends on heat transfer characteristics between the human and the surrounding environment. The thermal environment around a modelled manikin will be examined by numerical simulation of airflow, thermal radiation, heat conduction, moisture transport, solar radiation, and so on in a coupled way. This paper describes the concept of the computational thermal manikin and its first-stage development. Flow and temperature fields around the human body have been investigated by modelling the thermal manikin with computational fluid dynamics (CFD). The convective heat transfer characteristics of the modelled manikin are predicted for several types of flow field, i.e., stagnant flow, horizontal uniform flow, downward flow, and upward uniform flow. The CFD simulations are conducted using a low-Reynolds-number epsilon turbulence model. In order to model the complicated shape of the human body, a generalized curvilinear coordinate system (boundary fitted coordinates) is used. The results obtained agree well with previous experimental data.

Nielsen, P.V, Hoff, L., Pedersen, L.G. 1988. Displacement ventilation by different types of diffusers. *Proceedings of the 9th AIVC Conference*, Warwick.

This paper discusses the room air movement and ventilation effectiveness in different air distribution systems, mixing ventilation system and displacement ventilation system. It is indicated that mixing ventilation shows gradients in contaminant distribution in a room. It shows how the temperature gradient and temperature effectiveness are dependent on the location and type of heat sources in displacement ventilation. This paper also describes the flow from a low-level diffuser, which is suitable for a design procedure in displacement ventilation.

Nielsen, P.V. 1992. Air distribution system-Room air movement and ventilation effectiveness. *Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness (ISRACVE) Conference*, Tokyo, Society of Heating, Air-Conditioning and Sanitary Engineers of Japan.

Abstract: Ventilation effectiveness is strongly dependent on room air movement and contaminant source location. This paper shows that there are gradients in contaminant distribution in the room in case of mixing ventilation, and this will give rise to effectiveness different from 1.0. It is also shown that the location of the return openings may be very important compared with the small influence this location has on the velocity distribution in the room. The airflow rate in a room is often at a level where there is a low turbulence effect, and the ventilation effectiveness and the velocity distribution are strongly influenced by this effect. It is shown how the temperature gradient and temperature effectiveness are dependent in the location and type of heat sources in displacement ventilation. Concentration distribution and ventilation effectiveness are studied in a room with both stationary and movable sources. The paper describes the flow from a low-level diffuser, which is suitable for a design procedure in displacement ventilation.

Nielsen, P.V. 1996. Temperature distribution in a displacement ventilated room. *ROOMVENT '96, Yokohama, Japan,* Vol. 3, pp. 323-330.

Abstract: The vertical temperature gradient is normally given as a linear temperature distribution between a minimum temperature close to the floor and a maximum temperature close to the ceiling. The minimum temperature can either be a constant fraction of a load dependent difference or it can be connected to the volume flow to the room. This paper describes a new model which takes the different types of heat sources in the occupied zone as well as the characteristic Archimedes number of the flow into account. Full-scale experiments with different heat sources, such as distributed heat sources, sedentary persons, ceiling lights and a point heat source, have been used in the development.

Nielsen, P.V. 2000. Velocity distribution in a room ventilated by displacement ventilation and wall-mounted air terminal devices. *Energy and Buildings,* Vol. 31, Issue 3, pp. 179-187.

Abstract: This article describes experiments with wall-mounted air terminal devices. The airflow from an air terminal device influences the occupants' thermal comfort and, therefore, it is important to develop an expression for this flow in the occupied zone. The velocity at the floor is influenced by the flow rate to the room, the temperature difference and the type of diffuser. The flow is stratified at Archimedes numbers larger than four. The article gives expressions for the velocity distribution close to the floor. It is shown that openings between obstacles placed directly on the floor generate a flow similar to the air movement in front of a diffuser, and expressions for the velocity distribution in that situation are also given in the article.

Niemela, R., Koskela, H. 1996. Air flow patterns in a large industrial hall with displacement ventilation. *ROOMVENT '96, Yokohama, Japan,* Vol. 3, pp. 363-370.

Abstract: Air flow patterns and indoor climate were explored in a production hall, where containers and furnaces for the paper and pulp industry and chemical industries were fabricated. Welding fumes and other particulates generated by welding and related processes were aimed to control by the displacement ventilation. The supply air was introduced through seven low impulse diffusers mounted on the floor level against one long wall. The supply air distribution was characterized with tracer gas measurements using a step down procedure. However, the homogeneous initial concentration was not reached due to notable infiltration flows. Concentration of sulphur hexafluoride which served as a tracer was measured with two photoacoustic analysers connected to multipoint concentrations and thermal parameters were monitored at several sites in the hall. The local age values measured at different points in the occupied zone and at different heights indicated that the displacement flow behavior was achieved. This observation was supported by vertical temperature distribution. There were problems, however, in achieving the displacement flow patterns in the mornings when the ambient air in the hall was slightly cooler than the supply air.

Novoselac, A., Srebric, J. 2002. A critical review on the performance and design of combined cooled ceiling and displacement ventilation systems, *Energy and Buildings*, Vol. 34, Issue 5, pp. 497-509.

Abstract: This paper reviews the studies and design of cooled ceiling and displacement ventilation (CC/DV) systems in buildings. If properly designed, the combined CC/DV systems can provide better indoor air quality and thermal comfort levels compared to the widely used variable air volume (VAV) mixing systems. The cooling load removed by DV is a key design parameter. A low DV load has a positive effect on thermal comfort due to a small vertical temperature gradient, yet also has a negative effect on indoor air quality due to the increased mixing of room air. The impact of the room height on the temperature and contaminant concentration profiles is negligible in the occupied zone. The CC/DV systems are more effective in removing active contaminants (as indicated by CO_2) than passive contaminants (e.g. VOCs). The condensation risk on the chilled ceiling panel is high because of the high humidity ratio in the region close to the panel. To prevent condensation on the panel, it is important to properly control the system for transient regimes, such as startup and shutdown periods, and to minimize infiltration of humid outdoor air. Whether a CC/DV system may or may not reduce energy consumption depends on the supply air temperature, outdoor airflow rate, and cooling load. Therefore, it is necessary to develop design guidelines for CC/DV systems for U.S. buildings because the climate, building layout, and cooling load can be different from those studied elsewhere.

Olesen, B.W., Koganei, M., Holbrook, G.T., Seelen, J., Woods, J.E. 1994. Evaluation of a vertical displacement ventilation system. *Building and Energy*, Vol. 29, pp. 303-310.

The effectiveness of a vertical displacement ventilation system was evaluated when contaminants including tobacco smoke were present. Air supply was through a perforated floor and carpet. System performance was evaluated using ADPI (Air Diffusion Performance Index), percentage dissatisfied due to draft, vertical temperature difference, and air change, and contaminant removal indices. Gaseous contaminants were simulated with tracer gas. Cigarettes and occupants also generated particulates, CO_2, CO, and TVOC (total volatile organic compounds). Several combinations of supply air flow rate and thermal loads were evaluated. The risk of draft was found to be negligible. The air change effectiveness for the room varied from 126 to 145% and the contaminant removal effectiveness for the occupied zone varied from 80 to 700%.

Rees, S.J., Haves, P. 2001. A nodal model for displacement ventilation and chilled ceiling systems in office spaces. *Building and Environment*, Vol. 36, Issue 6, pp. 753-762.

Abstract: A nodal model has been developed to represent room heat transfer in displacement ventilation and chilled ceiling systems. The model uses precalculated air flow rates to predict the air-temperature distribution and the division of the cooling load between the ventilation air and the chilled ceiling. The air movements in the plumes and the rest of the room are represented separately using a network of 10 air nodes. The values of the capacity rate parameters are calculated by solving the heat and mass balance equations for each node using measured temperatures as inputs. Correlations between parameter values for a range of cooling loads and supply air flow rates are presented.

REHVA. 2002. Displacement Ventilation in Non-Industrial Premises, ed. Skistad, H. et al.

Saeteri, J. 1992. A breathing manekin for measuring local ventilation effective-ness. *ROOMVENT '92,* Aalborg.

The author simulated the heat loads from humans and equipment using various kinds of point or surface sources. A manikin was tested in a laboratory chamber. Tests with the manikin and a test person showed that convective flow of a person improves the quality of the air in the breathing zone when displacement ventilation is used.

Sandberg, M., Blomqvist, C. 1989. Displacement ventilation systems in office rooms. *ASHRAE Transactions,* Vol. 95, No. 2.

Abstact: This paper summarizes results of measurements carried out in an office room and showed that there are limits to this type of ventilation. There are specific requirements in the design of supply air terminals in order not to exceed comfort criteria with regard to acceptable air velocities. Furthermore, the temperature gradient associated with this type of ventilation puts a restriction on the maximum heat load. Ventilation by displacement gives rise to larger room-average ventilation effectiveness than traditional mixing systems. However, with the flow rates normally supplied to office rooms, the concentration in the breathing zone is the same as with traditional mixing systems.

Seppanen, O.A., Fisk, W.J., Eto, J., Grimsrud, D.T. 1989. Comparison of conventional mixing and displacement air-conditioning and ventilating systems in U.S. commercial buildings. *ASHRAE Transactions,* Vol. 95, No. 2.

Abstract: This paper evaluates displacement air distribution systems and compares their performance with the performance of traditional variable and constant air flow systems in U.S. office buildings. The loads of a typical large U.S. office building were calculated for four representative U.S. climates with the DOE-2.1C building simulation program. It states that the results indicate that displacement systems generally yield superior air quality and thermal comfort compared to conventional systems with air recirculation. Treats energy consumptions and costs.

Sowell, E.F., Hittle, D.C. 1995. Evolution of building energy simulation methodology. *ASHRAE Transactions*, Vol. 101, pp. 850-855.

Abstract: Public domain building load calculation and energy analysis programs developed along two major paths with respect to calculating air conditioning loads. One approach used the so-called weighting factor method, which calculates instantaneous space energy gains and then smears them out over time using weighting factors. The other approach relied on a surface-by-surface heat balance. In this scheme, a radiative, conductive, and convective heat balance is done on each room surface (both inside and outside). The air conditioning load is determined by computing how much energy is convected into the room air from surfaces, lights, people, and equipment. Both methods have advantages and disadvantages, especially with respect to the connection between air conditioning load calculation and system performance simulation. For example, room-temperature weighting factors allow for the effect of system performance on air conditioning loads (i.e., insufficient cooling capacity) to be estimated. When the heat balance method is used, the relationship between heat removal capacity and room temperature must be specified during load calculation. Contrasts the weighting factor and heat balance methods, focusing on the assumption in each method, the limitations of each, and how each method evolved in public domain software. New alternatives are presented.

Straub, H.E. 1962. What you should know about room air distribution? *Heating, Piping & Air Conditioning,* January, pp. 209-220.

This paper deals with room air distribution questioning what criteria must be satisfied; how principles can be employed; how supply outlets perform; and what the general selection considerations are. It includes a step-by-step procedure of applying principles of air distribution formulated as a result of research at the University of Illinois, and also contains data for determining what local draft conditions mean in terms of discomfort.

Stymne, H.,Sandberg, M., Mattsson, M. 1991. Dispersion pattern of contaminants in a displacement ventilated room. *Proceedings of the 12th AIVC Conference,* Ottawa.

The authors used a passive tracer technique in an experimental study of the distribution of contaminants in a room with displacement ventilation. Heated metallic bodies are used to simulate humans. It is shown that air quality demand control of the supply air flow rate is a suitable means of securing the excellent air quality possible in a displacement ventilated room.

Svensson, A.G.L. 1989. Nordic experiences of displacement ventilation systems. *ASHRAE Transactions,* Vol. 95, No. 2.

Abstract: This paper points out that ventilation systems utilizing the displacement principle currently have 25% of the market in new office buildings in Nordic countries. It discusses the current state of displacement systems with regard to air exchange

efficiency, ventilation efficiency and thermal comfort. It also discusses trends in the development of the systems and predicts a bright future for this technique of supplying air at low velocity.

Taki, A.H., Loveday, D.L., Parsons, K.C. 1996. The effect of ceiling temperatures on displacement flow and thermal comfort: Experimental and simulation studies. *ROOMVENT '96,* Yokohama, Japan, Vol. 3, pp. 307-314.

Abstract: This paper presents experimental results in the effect of ceiling surface temperatures in the vertical air temperature profile within a displacement ventilation environment. Further, the effect of the ceiling temperature on human thermal comfort is assessed using a simulation program. The implications for the future design of such environments are discussed.

Tanabe, S., Kimura, K. 1996. Comparisons of ventilation performance and thermal comfort among displacement, under floor and ceiling based air distribution systems by experiments in a real sized office chamber. *ROOMVENT '96,* Yokohama, Japan, Vol. 3, pp. 299-306.

Abstract: Performance of displacement, underfloor, and ceiling based air distribution systems were evaluated based in the age of air, contaminant concentration, and thermal comfort. Measurements to evaluate indoor environment were conducted in an office type of chamber. In this experiment a thermal manikin was also used to examine thermal comfort. The underfloor air conditioning system performed slightly better than the conventional ceiling diffuser system in ventilation efficiency. For the displacement system, the local air change index at respiration zone turned out nearly 1.6, but a large vertical temperature difference was found with low supply air volume, which might cause local discomfort.

Wyon, D.P., Sandberg, M. 1990. Thermal manikin prediction of discomfort due to displacement ventilation. *ASHRAE Transactions,* Vol. 96, Pt. 1.

Abstract: Problems were noted with displacement ventilation in offices where people have to sit still and experience cold discomfort for the legs and feet in conjunction with heat discomfort at head height. This paper describes an empirical study of simulated winter and summer operating conditions using human subjects at the National Swedish Institute for Building Research. The thermal manikin system VOLTMAN for the assessment of non-uniform thermal conditions was exposed to the same conditions as the subjects to investigate the relationship between local heat flow and sensations of thermal discomfort. Results were presented as diagrams and tables and were discussed. Suggestions were provided for improving thermal comfort with displacement ventilation.

Xing, H., Hatton, A., Awbi, H.B. 2001. A study of the air quality in the breathing zone in a room with displacement ventilation. *Building and Environment,* Vol. 36, Issue 7, pp. 809-820.

Abstract: This paper is concerned with the difference in the air quality that is perceived by the occupants (breathing zone) and that existing in the occupied zone as a whole. An

environmental chamber with a displacement ventilation system has been used to carry out the measurements with the presence of a heated mannequin and other heat sources. Measurements of the age of air distribution, the air exchange index and the ventilation effectiveness were carried out at different points in the chamber for different room thermal loads. CFD simulations were also carried out for the purpose of flow visualization as well as the calculation of air velocity, temperature and age of air distribution. In addition, CFD simulations were carried out to study the effect of changing the airflow rate to the chamber and the position of the air inlet to extend the range of parameters. The results from the CFD simulations were compared with those from measurements and good agreement was obtained in most cases.

Xing, H., Hazim, B.A. 2002. Measurement and calculation of the neutral height in a room with displacement ventilation. *Building and Environment*, Vol. 37, Issue 10, pp. 961-967.

Abstract: This paper investigates the relationship between the neutral height for air distribution and the ventilation load in a room with displacement ventilation. An environmental chamber equipped with a displacement ventilation system has been used to carry out the neutral height measurements with the presence of a heated mannequin and other heat sources in the chamber. The total room load used varied from 104 to 502 W, i.e., corresponding to a ventilation load from 10 to 60 W/m2. The prediction of the neutral height was based on the plume theory. Comparison between the experimental data and the predictions showed good agreement. The prediction also showed that the human body could draw uncontaminated fresh air from the lower zone, which improves the air quality in the breathing zone.

Yuan, X., Chen, Q., Glicksman, L.R. 1998. A critical review on displacement ventilation. *ASHRAE Transactions,* Vol. 104, Pt. 1, pp. 78-90.

Abstract: This paper reviews several aspects of the performance of displacement ventilation: temperature distribution, flow distribution, contaminant distribution, comfort, energy and cost analysis, and design guidelines. Ventilation rate, cooling load, heat source, wall characteristics, space height, and diffuser type have major impacts on the performance of displacement ventilation. Some of the impacts can be estimated by simple equations, but many are still unknown. Based on current findings, displacement ventilation systems without cooled ceiling panels can be used for space with a cooling load up to 13 Btu/(h*ft^2) (40 W/m^2). Energy consumed by HVAC systems depends on control strategies. The first costs of the displacement ventilation system are similar to those of a mixing ventilation system. The displacement system with cooled ceiling panels can remove a higher cooling load, but the first costs are higher as well. The design guidelines of displacement ventilation developed in Scandinavian countries need to be clarified and extended so that they can be used for U.S. buildings. This paper outlines the research needed to develop design guidelines for U.S. buildings.

Zhang Lin, Chow, T.T., Tsang, C.F., Fong, K.F., Chan, L.S. 2005. CFD study on effect of the air supply location on the performance of the displacement ventilation system, *Building and Environment*, Volume 40, Issue 8, pp 1051-1067.

Abstract: The purpose of this paper is to investigate using a numerical simulation (computational fluid dynamics or CFD) the effect of the air supply location on the design and performance of the displacement ventilation (DV) system. The results are reported in terms of thermal comfort and indoor air quality. The study focuses on the typical Hong Kong office under local thermal and boundary conditions. This includes the high cooling load used in Hong Kong. Several pollutants typically found in the office, such as carbon dioxide and volatile organic compounds (VOCs), were investigated. The results indicate that the supply should be located near the center of the room rather than to one side of the room. This will provide a more uniform thermal condition in the office. The DV system was found to be effective in dispersing VOCs within an office environment for all cases studied. The exhaust was found to have minimal effect on the thermal comfort. For a DV system in Hong Kong, it is possible to use 100% fresh air without extra energy consumption.

Zhivov, A.M., Rymkevich, A.A. 1998. Comparison of heating and cooling energy consumption by HVAC system with mixing and displacement air distribution for a restaurant dining area in different climates. ***ASHRAE Transactions,*** **Vol. 104, Pt. 2.**

Abstract: This paper discusses the different ventilation strategies to improve indoor air quality and to reduce HVAC system operating costs in a restaurant with nonsmoking and smoking areas and a bar. A generic sitting-type restaurant is used for the analysis. Prototype designs for the restaurant chain with more than 200 restaurants in different U.S. climates were analyzed to collect the information on building envelope, dining area size, heat and contaminant sources and loads, occupancy rates, and current design practices.